POINTABLE OPTICAL TRANSCEIVERS FOR FREE SPACE OPTICAL COMMUNICATION

Technical Field

The invention pertains to methods and apparatus for free space optical communication.

Related Applications

This application claims the benefit of U.S. Provisional Patent Application 60/432,197, filed December 9, 2002, and is a continuation-in-part of U.S. Patent Application 10/020,518, filed December 14, 2001, both of which are incorporated herein by reference.

Background

While guided wave optical systems have become commonplace in telecommunications, such systems exhibit several practical limitations. Installation of such systems in existing buildings can be disruptive and labor intensive, and in some cases cannot be economically configured to reach all building areas for which optical communication services are desired. Communication applications between two or more buildings or other locations typically require underground installation of optical cables in existing utility tunnels or burial in newly dug trenches. Such installations can be slow and expensive. In addition, reconfiguration of a guided wave communication system can be difficult as additional optical fiber or other waveguide must be installed to reach any newly selected locations. As a result, an installed communication system can require expensive upgrades.

Free space optical communication systems do not exhibit the limitations associated with the installation and maintenance of guided wave optical communication

systems. Such systems include optical transmitters and receivers that are configured to deliver and receive optical signals propagating in free space, and waveguides are not needed to connect the transmitter and receiver. In addition, such transmitters and receivers can be portable and readily adapted to a user's varying communication requirements.

While free space optical communication systems have numerous advantages, such systems typically have several drawbacks. Transmitter and receiver locations can be easily changed, but a transmitter and an associated receiver must be located within a line of sight and selection of a particular transmission or reception direction requires careful alignment. Transceivers are also subject to mechanical disturbances that can degrade an existing alignment because transceivers are frequently placed in exposed locations. For these reasons, improved free space optical communication systems, methods, and apparatus are needed.

Summary

Free space optical systems can use optical transceivers to transmit and receive optical signals. Optical transceivers can be configured to receive optical signals from a source such as a modulated laser diode or other source, and process the optical signal for free space transmission. Such transceivers can also be configured to receive optical signals propagating in free space and to process such signals for delivery to an optical detection system that includes an optical detector such as a photodiode or avalanche photodiode. In representative examples, optical transceivers comprise a diffractive optical element (DOE) configured to receive an input optical beam. A reflective surface is configured to receive at least a portion of the input optical beam from the DOE and direct the portion to an optical detector. A mount is provided for the reflective surface and is configured to rotate the reflective surface with respect to the DOE and thereby select an orientation of the reflective surface. The orientation of the reflective surface

can be associated with, for example, reception of the input optical beam from a selected direction or transmission to a selected direction.

In representative examples, optical transceivers comprise a diffractive optical element (DOE) configured to transmit an input optical beam. A reflective surface is configured to receive the transmitted optical beam from the DOE and direct a reflected optical beam to the DOE. A mount is configured to rotate the reflective surface so that the DOE diffracts at least a portion of the reflected optical beam to an optical detector. According to additional representative examples, optical transceivers comprise an index-matching material situated at the reflective surface, and extending from the reflective surface to the DOE. In other examples, transceivers include an optical support having a first surface configured to receive the portion of the input optical beam reflected by the reflective surface and to direct the portion to an output surface. In further examples, the DOE is configured to diffract at least a portion of the optical beam received from the reflective surface to an output surface.

Optical transmitters comprise a diffractive optical element (DOE) configured to receive an output optical beam and a reflective optical element having a reflective surface configured to receive at least a portion of the output optical beam from the DOE and direct the portion to a recipient. A mount is configured to rotate the reflective optical element and select an orientation of the reflective surface, wherein the orientation of the reflective surface is associated with selection of a transmission direction. In other examples, optical transmitters comprise an index-matching material situated at the reflective surface and extending to the DOE. According to other representative examples, optical transmitters further comprise an optical support having a first surface configured to direct at least a portion of the output optical beam to the DOE. In further examples, the DOE is configured to diffract at least a portion of the output optical beam received from the first surface of the optical support to the reflective surface.

Optical transceivers comprise a diffractive optical element (DOE) and a reflective surface configured to receive an optical beam from the DOE and direct a reflected portion to the DOE. The reflective surface is rotatable with respect to the DOE for selection of, for example, a communication direction. According to representative examples, the DOE is bonded to an optical support and is configured to direct the optical beam to an output surface of the optical support based on a wavelength associated with the optical beam. In additional examples, the optical support includes a surface configured to communicate the optical beam between the DOE and the output surface of the optical support. In additional representative embodiments, the surface of the optical support is configured to communicate the optical beam between the DOE and the output surface by total internal reflection. In other examples, a communication direction is selectable based on a rotation angle of the reflective surface with respect to the DOE, or a rotation angle of the reflective surface with respect to the DOE and the output surface.

Optical transceivers comprise an optical support having a first surface configured to be situated adjacent a window, a second surface, and a coupling surface. A diffractive optical element (DOE) is situated adjacent the second surface. A reflective optical surface and an optical mount that is adjustable to select an orientation of the reflective optical surface with respect to that DOE are provided so that the DOE and the reflective optical surface direct a light flux received from the first surface to the coupling surface, or direct a light flux from the coupling surface to the first surface. In other examples, the second surface comprises a reflective region configured to direct a light flux to the coupling surface or to the DOE. In some examples, the reflective region includes a reflective coating or is situated to provide total internal reflection. In other representative examples, networks comprise at least two computer devices, and at least two such optical transceivers configured to interconnect the at least two computer devices.

Communication methods comprise receiving an optical signal beam and directing the optical signal beam to a diffractive optical element (DOE). At least a portion of the optical signal beam received from the DOE is reflected back to the DOE. The DOE diffracts a portion of the optical signal beam received from the reflective surface to an optical detector. According to representative examples, a communication direction is selected based on a rotation angle of the reflective surface with respect to the DOE. In other representative examples, the step of selecting a communication direction includes adjusting an orientation angle of the reflective optical surface with respect to the communication direction.

Methods of processing an optical signal comprise directing the optical signal to a diffractive optical element (DOE), receiving the optical signal from the DOE, and reflecting the optical signal back to the DOE. At least a portion of the optical signal reflected to the DOE is diffracted to a surface of an optical support so that the portion propagates in the optical support at an angle greater than a critical angle with respect to the surface. According to other representative examples, the optical signal is directed to a surface of the optical support having optical power that is based on a surface curvature.

These and other features and advantages are set forth below with reference to the accompanying drawings.

Brief Description of the Drawings

FIG. 1 is a block diagram of a free space optical communication system illustrating communication between two buildings.

FIG. 2 is a schematic diagram of an optical transceiver configured for use in a free space optical communication system.

FIG. 3 is a schematic diagram of an optical transceiver configured for use in a free space optical communication system.

FIG. 4 is a schematic diagram of an optical transceiver configured for use in a free space optical communication system.

FIG. 5 is a schematic diagram of an optical transceiver configured for use in a free space optical communication system.

FIG. 6 is a schematic diagram of an optical transceiver configured for use in a free space optical communication system.

FIG. 7 is a schematic diagram of an optical transceiver configured for use in a free space optical communication system.

FIG. 8 is a schematic diagram of an arrangement for recording a hologram for use in an optical transceiver.

FIG. 9 is a diagram illustrating an optical transceiver configured for mounting to a window.

FIGS. 10A-10B are schematic diagrams of optical mounting and alignment mechanisms for mounting an optical transceiver to a window.

FIG. 11 is a schematic diagram of an optical transceiver that includes a mirror that directs an optical signal to a hologram or other diffractive element.

FIG. 12 is a schematic diagram of an optical transceiver that includes a reflection hologram.

FIG. 13 is a schematic diagram of an optical transceiver that includes a hologram situated on a curved surface.

FIG. 14 is a schematic diagram of an optical transceiver that includes first and second holograms that direct an optical beam toward a coupling surface and converge, the optical beam at the coupling service, respectively.

FIGS. 15-16 are perspective views of optical transceivers configured to transmit and receive spatially separated optical signals.

FIG. 17 is a sectional view of an optical transceiver situated at a dual pane window and that is adjustable using a gimbal mount.

FIG. 18 is a sectional view of an optical transceiver situated at a dual pane window that includes a curved mirror that is adjustable using a gimbal mount.

FIG. 19 is a schematic diagram of an optical transceiver that includes a reflection hologram.

FIG. 20 is a schematic diagram of an optical transceiver configured for use in a free space optical communication system.

FIG. 21 is a schematic diagram of an optical transceiver that includes an adjustable reflector.

Detailed Description

With reference to FIG. 1, a communication system is configured to transmit data, voice, or other information between buildings 102, 104. An optical transceiver 106 is situated at or near a window 107 and is configured to transmit optical signals produced by an optical transmitter/receiver module 108 to the building 104. The optical transceiver 106 is also configured to receive optical signals from the building 104 and direct the received optical signals to the optical transmitter/receiver module 108. The received optical signals are converted to electrical signals at the transmitter/receiver module 108 or can be deliver by an optical fiber or other optical apparatus to a server 110 that includes electrical-to-optical and/or optical-to-electrical conversion circuitry. The associated electrical signal is then processed by the server 110 or other computer or network element.

An optical transceiver 112 is similarly configured at the building 104 for communication with the building 102. The optical transceiver 112 is situated at or near a window 113 and is configured to transmit optical signals to and receive optical signals from the optical transceiver 106. Received optical signals are directed to a transmitter/receiver module 114 that is in communication with a server 116 or other computer or network element. The transmitter/receiver module 114 can include optical-

to-electrical converters or can be configured to transmit optical signals to and from optical-to-electrical conversion circuitry located at, for example, the server 116.

Representative optical transceiver configurations are illustrated schematically in FIGS. 2-7, 9, and 11-13. For convenience, surface curvatures are shown for purposes of illustration only and it will be apparent how surface curvatures can be selected and configured. In addition, multiple surfaces are shown for producing optical beam convergence and focusing, but surfaces can also be selected to produce beam divergence and defocusing as well as aberration correction and various telescope configurations can be adapted for such use. Descriptions of example transceiver configurations are provided with reference to transceiver use as a transmitter, receiver, or both. The example transceivers can generally be used for both applications and for convenience, are described with reference to transmitter or receiver use only. Optical surfaces through which optical signals are received from an optical source for transmission, or delivered to an optical detection system are referred to as coupling surfaces. Examples are described with reference to holograms, but other diffractive optical elements can be used. In some examples, some surfaces are tilted with respect to others, but nevertheless remain approximately parallel. For convenience, tilted, substantially parallel surfaces are defined as surfaces that are tilted at angles of less than about 20 degrees with respect to each other.

In some examples, optical signals propagate within an optical support or a prism at angles with respect to one or more surfaces such that the optical signals are totally internally reflected. As used herein, such optical signals are referred to as propagating at angles greater than a critical angle with respect to a surface. While such critical angles generally depend on a ratio of refractive indices, and as used herein an index of refraction of an optical support material and an index of refraction of air can be used to determine critical angles.

A representative optical transceiver 200 configured to transmit and receive optical signals is illustrated in FIG. 2. The transceiver 200 includes a hologram 202

applied to a surface 204 of an optical support 206. The hologram 202 is configured to direct or diffract an input optical beam 208 to a reflective surface 210. The reflective surface 210 is illustrated for convenience as a spherical surface but the reflective surface 210 typically corresponds to an off-axis section of a parabola and is configured to direct a diffracted optical beam 212 to converge at or near a surface 214. Other shapes can be used for the surface 210 such as on- or off-axis parabolic, elliptical, hyperbolic, spherical, aspheric, or toric sections. Optical power can also be provided by the hologram 202. To enhance reflectivity, the surface 210 can be coated with a reflective coating such as a metallic coating of aluminum, silver, gold, nickel, chromium, rhodium, or a combination of these or other metals. Dielectric coatings can also be used such as multilayer coatings that include alternating layers of high and low refractive index materials. Alternatively, a hologram can be provided.

The optical support 206 can be made of various optical materials including plastic optical materials such as acrylics, polycarbonates, optical glasses, fused silica, and other optical materials. The optical material is generally selected based on considerations such as cost and optical properties such as transmittance in a wavelength range over which a transceiver is to be used. A wavelength range in which optical communication components are readily available is between about 500 nm and about 1700 nm, but other wavelengths can be used. In some applications, wavelength ranges are selected based on eye safety considerations or on building window transmittances. Surfaces of the optical support 206 such as the surface 210 and the surface 214 can be formed by polishing, molding processes such as injection molding, casting, machining or other process. In addition, such surfaces can be defined by additional optical elements that are attached to the optical support 206 by, for example, an optical epoxy or other adhesive. As a specific example, a flat optical surface can be provided by attachment of an optical window or other optically flat substrate to the optical support. By providing optical surfaces on the optical support 206, a mechanically and optically robust transceiver configuration is obtained.

As shown in FIG. 2, the diffracted beam 212 is produced by the hologram 202 but other optical elements can be used instead of the hologram 202. For example, replica diffraction gratings or ruled diffraction gratings can be used, and such gratings can be blazed for improved diffraction efficiency. Ronchi rulings can be used as well, and optical power can be included in the hologram 202 so that some focusing of the diffracted beam 212 is produced. As used herein, a hologram refers to a recorded optical interference pattern, and can be configured for use in reflection or in transmission.

The diffracted optical beam 212 is converged by the surface 210 and delivered to an optical fiber module 216 situated at the surface 214. According to the example of FIG. 2, the optical fiber module 216 includes a fiber connector bulkhead adapter 217 that receives an optical fiber 218 so that the converged optical signal is delivered to the optical fiber 218. Typically, an end of the optical fiber 218 is connectorized for attachment to the bulkhead adapter 217, and in a specific example, the fiber 218 is provided with a so-called FC type connector and the bulkhead adapter 217 is an FC adapter.

The optical transceiver 200 is configured for transmission and reception of optical signals. An optical signal can be delivered by the optical fiber 218 to the surface 210 and to the surface 204 and outwardly directed by the hologram 202. Thus, the optical transceiver can server either as a transmitting transceiver or a receiving transceiver.

A surface 220 of the optical support 206 is configured to be non-parallel with respect to the surface 204. Providing a relative tilt between these surfaces reduces the magnitude of optical signals that experience one or more reflections by the surfaces 204, 220 or other surfaces that are undesirably delivered to optical receiver modules. In addition, to reduce unwanted optical signals, portions of the surfaces 204, 210, 214, 220, and other surfaces can be provided with absorbing or anti-reflection optical coatings. Such coatings can be configured to absorb or reduce reflections at

wavelengths associated with stray light. As shown in FIG. 2, the surface 220 is configured so that the optical support 206 tapers toward the surface 214, but in other examples the surface 220 can be configured so that the optical support tapers toward the surface 210.

The hologram 202 is configured to direct selected optical signals to the surface 210 and to permit unselected optical radiation to propagate towards the surface 220. Such unselected signals can be absorbed with an absorbing coating situated on the surface 220 or the surface 220 can be provided with an antireflection coating to increase the portion of the unselected radiation that exits the transceiver 206. In addition, as shown in FIG. 2, the hologram 202 is configured to direct signal light at a wavelength of about 783 nm at an angle of about 36.2 degrees with respect to a line perpendicular to the surface 204. For this angle, a hologram thickness of about 20 μm is selected to reduce polarization dependence of the diffraction efficiency of the hologram 202. (Hologram diffraction efficiency is generally a function of light polarization direction with respect to the fringe direction recorded in the hologram.)

The diffracted optical signal 212 can propagate within the optical support 206 at an angle with respect to the surface 204 that is greater than the critical angle. Thus, stray light can accompany the diffracted optical signal only if diffracted by the hologram 202. Generally the hologram 202 is configured to diffract only selected wavelengths (and not wavelengths associated with stray light or background light), so that little unwanted light accompanies the desired signal light. In particular, the hologram 202 can appear clear or highly transmissive at some wavelengths and have a high diffraction efficiency at a selected communication wavelength. Because the desired signal light is generally received through a small aperture (such as a core of a multimode fiber or a single mode fiber), non-signal wavelengths that are diffracted at other angles are not efficiently coupled for detection or transmission.

With reference to FIG. 3, an optical transceiver 300 includes a hologram 302 or other light directing element situated at or bonded to a surface 304 of an optical support

306. The optical transceiver 300 is configured to receive an optical signal 308 through the hologram 302, and to direct a diffracted or otherwise deflected portion 312 of the optical signal to a surface 310 and to a surface 309. The optical support 306 includes a first portion 314 and a second portion 316 that are bonded at an interface surface 318. A surface 320 is configured to reduce multiple reflections within the optical support 306 and direct any such reflected light away from a collection region 322.

With reference to FIG. 4, an optical transceiver 400 includes a hologram 402 configured to direct a portion 412 of an input optical signal 408 toward a first curved surface 410 and a second curved surface 411. The surfaces 410, 411 are selected to converge the portion 412 at or near a surface 414. As shown in FIG. 4, an optical support 406 includes two surfaces (the surfaces 410, 411) that have optical power and serve to converge or otherwise focus the signal portion 412.

With reference to FIG. 5, an optical transceiver 500 includes a hologram 502 that is configured to direct a diffracted portion 512 of an input optical signal 508 to a planar surface 510 and to a curved surface 511 that is configured to converge the diffracted portion 512, typically at or near a surface 509. The surfaces 510, 511 are conveniently provided on an optical support 506, but the optical support 506 can be configured as two or more pieces bonded together. In addition, an unused portion 519 of the optical support 506 can be removed.

Additional illustrative embodiments are illustrated in FIGS. 6-7. Referring to FIG. 6, a transceiver 600 includes a Ronchi ruling 602 configured to direct an optical signal portion 612 of an input optical signal 608 to a curved surface 610 and to an output surface 614 of an optical support 606. A rear surface 611 is arranged approximately parallel to a front surface 604. The shape or curvature of the curved surface 610 is selected to converge the optical signal portion 612.

Referring to FIG. 7, an optical transceiver 700 includes a first surface 704 that supports a hologram 702 that is configured to direct a signal portion 712 to a curved surface 710. The curved surface 710 is selected to converge the signal portion 712 and

to direct the signal portion 712 to a surface 714 that reflects the signal portion 712 back to the surface 710. As shown in FIG. 7, the signal portion 712 converges at or near the surface 710 at a location 717 and can be collected by an optical system or an optical fiber and delivered to an electrical system for conversion into an electrical signal.

Several example optical transceivers are described above with reference to receiving optical signals. These example transceivers also serve as transmitters in which a converged optical signal is processed or collimated by one or more curved surfaces and then directed along an output direction by a hologram or other optical element. In additional examples, optical transceivers are configured so that diffracted or deflected optical signal portions are reflected by one or more surfaces, and can be reflected by a single surface one or more times. In other alternative examples, two holograms are attached to a single optical support so that one is used for transmission and the other is used for reception. In such examples, separate optical fibers can be provided for delivering optical signal to the transceivers and obtaining optical signals from the transceivers.

An arrangement for recording a hologram for use in the optical transceivers described above is illustrated in FIG. 8. Spatially filtered optical beams 802, 804 are directed to a surface 806 of a prism 808. The optical beams interfere at a holographic recording element 810 situated at a surface 811 of the prism 808. The holographic recording element 810 typically includes a photosensitive layer and a transparent support layer. Alternatively, a photosensitive layer can be applied directly to the surface 811. The holographic recording element is placed on the surface 811 and reflections by the holographic recording element 810 are reduced by index matching to the surface 811 with, for example, an index-matching liquid. A rectangular prism 812 is placed on the holographic recording element 810 and index matched. A back surface 814 of the rectangular prism 812 is coated with an absorbing coating to reduce reflections.

Optical transceivers are typically configured for use with optical signals in wavelength ranges for which common holographic recording materials are not the most sensitive. Accordingly, hologram recording is configured based on the difference in recording wavelength and playback wavelength. In a representative example, the recording wavelength is a wavelength associated with an argon ion laser (for example, 488 nm or 514.5 nm) and the playback wavelength is about 785 nm. Non-standard holographic materials that are more sensitive at playback wavelengths can also be used. In some examples, holograms such as the hologram 202 are recorded using HRF-600-X113-6*0.5 photopolymer available from DuPont Corporation, Wilmington, Delaware. In addition, shrinkage of holographic materials can be compensated and as noted above, a thickness of a holographic recording material can be selected to reduce polarization dependence of hologram diffraction efficiency. Index of refraction modulation in a hologram can be associated with polarization dependence of diffraction efficiency, and selection of an index modulation permits control of polarization dependence. Such holographic configurations are described in, for example, H. Kogelnik, "Coupled Wave Theory for Thick Holograms," Bell Sys. Tech. J. **48**:2909-2947 (1969), which is incorporated herein by reference.

A mounted optical transceiver 900 is illustrated in FIG. 9. The transceiver 900 includes an optical support 902 and a mirror section 903 that is attached to the optical support 902 and that defines a reflecting surface for input/output optical signals. Optical signals are delivered to the optical transceiver 900 at a fiber connector adapter 910. The transceiver 900 is aligned with alignment mounts 904, 906, 908 that include respective adjustment mechanisms 920, 922, 924 and surface mounting portions 930, 932, 934. The surface mounting portions 930, 932, 934 are configured for mounting to various surfaces such as a office window using an adhesive, an adhesive pad, or other method. The adjustment mechanisms 920, 922, 924 are attached to the optical support 902 with an adhesive. Alternatively, mounting holes, surfaces, tabs, or other features can be provided as part of the optical support 902, particularly for plastic optical

supports. Mounts for optical transceivers are preferably configured for compactness, ease of installation, and to be unobtrusive after installation and the arrangement of FIG. 9 permits easy installation and alignment.

FIGS. 10A-10B are schematic diagrams illustrating alignment and mounting mechanisms suitable for use in the apparatus of FIG. 9. Referring to FIG. 10A, an alignment mechanism 1000 includes a groove plate 1006 configured to be bonded with an adhesive layer 1004 to a window 1002. A groove 1007 is defined in the groove plate 1006 and is configured to receive an adjustment screw 1008 of an adjustment plate 1009. A spring 1011 or the like is situated to urge the adjustment plate 1009 toward the groove plate 1006 so that the adjustment screw 1008 contacts the groove plate 1006. A surface 1010 of the adjustment plate 1009 is configured for mounting to an optical transceiver.

Referring to FIG. 10B, an alignment mechanism 1020 includes a slot plate 1026 configured to be bonded with an adhesive layer 1024 to a window 1022. A slot 1027 is defined in the plate 1026 and is configured to receive an adjustment screw 1028 of an adjustment plate 1029. A spring 1031 or the like is situated to urge the adjustment plate 1029 toward the plate 1026 so that the adjustment screw 1028 contacts the plate 1026. A surface 1030 of the adjustment plate 1029 is configured for mounting to an optical transceiver.

The alignment mechanisms of FIGS. 10A-10B are based on so-called kinematic mounts, but other alignment mechanisms can be based on flexure mounts or gimbal mounts. Such mechanisms can be provided individually for attachment to an optical transceiver and to a window through which a transceiver is to send or receive optical signals. Using such mounts permits an optical transceiver at a selected location to be configured to communicate with an optical transceiver at another location.

With reference to FIG. 11, an optical transceiver 1100 is attached to a first window 1102 and is configured to send and receive optical signals through the first window 1102 and a second window 1104 along a path defined by ray directions 1106,

1107. The optical transceiver 1100 includes an optical support 1110 and a hologram 1112. An input optical signal propagates through the windows 1102, 1104, the optical support 1110, and the hologram 1112 and is reflected by a steering mirror 1114 back to the hologram 1112. The mirror is configured to be rotatable about gimbals 1116 and in one embodiment is immersed in an index-matching material 1118 such as an index-matching liquid that is retained by a container 1120. A curved reflective surface 1122 is provided on the optical support 1110, and typically corresponds to an off-axis section of a parabola. The input optical signal received by the transceiver 1100 is directed to the steering mirror 1114 that is aligned with the gimbals 1116 so that a diffracted portion of the reflected optical signal is directed to the parabolic mirror 1122 and converged to an output 1124. By adjustment of the steering mirror 1114, optical signals from a variety of remote locations can be detected. Similarly, an optical signal applied to the output 1124 can be delivered to a selected remote location by adjustment of the steering mirror 1114. The mirror can also be configured to be steered about with, for example, a set of mutually orthogonal gimbals for two dimensional coverage.

An example optical transceiver 1200 using a reflective hologram 1202 is illustrated in FIG. 12. The hologram 1202 is attached to a surface 1206 of an optical support 1207 and is configured to direct at least a portion 1212 of an input optical signal 1208 to a curved reflective surface 1210 and to a coupling surface 1209. As shown in FIG. 12, a surface 1220 through which optical signals enter and/or exit the optical support 1207 is tilted with respect to the surface 1206. For convenience, refraction of the input optical signal 1208 at the surface 1220 is not shown but the optical signal 1208 need not enter the optical support 1208 perpendicularly to the surface 1220. The hologram 1202 is typically configured to deflect optical signals of selected wavelengths to the curved reflective surface 1210 and transmit other wavelengths. In addition, the deflected optical signal portion 1212 typically propagates at an angle greater than a critical angle with respect to the surface 1206.

An optical transceiver 1300 illustrated in FIG. 13 includes a hologram 1302 situated on a curved surface 1305 of an optical support 1306. The hologram 1302 is configured to deflect a portion 1312 of an input optical beam 1308 to a reflective surface 1310 and to coupling surface 1309. As shown in FIG. 13, an optical beam 1318 associated with, for example, vision through the optical transceiver 1300 with optical radiation at wavelengths transmitted by the hologram 1302.

With reference to FIG. 14, an optical transceiver 1400 includes holograms 1402, 1410 situated at respective surfaces 1403, 1411 of an optical support 1406. The hologram 1402 is configured to direct a portion 1412 of the optical beam 1408 to the hologram 1410 that converges or partially converges the portion 1412 at, near, or through a coupling surface 1414. The optical transceiver 1400 does not include curved optical surfaces that provide optical power but instead includes the hologram 1410. While the hologram 1402 can be configured to direct the optical beam 1408 to the surface 1411 as well as converge the optical beam 1408, providing two holograms simplifies hologram fabrication.

With reference to FIG. 15, an optical transceiver 1500 is retained by a pointing assembly 1502 that is configured to direct optical signals to or receive optical signals from a selected location. The optical transceiver 1500 includes an optical support 1504 having an input/output surface 1506 and a focusing surface 1508. A transmit hologram and a receive hologram can be provided on the surface 1506, or a single hologram can be used. The transmit hologram directs an optical signal from a prism portion 1510 to a portion 1508a of the focusing surface 1508 and that is then transmitted through the surface 1506. Received optical signals are directed by an input hologram to a portion 1508b of the focusing surface 1508 and then directed to the prism portion 1510. The portions 1508a, 1508b are typically independently configured to direct, focus, or otherwise process received and transmitted optical signals. Optical signals can be coupled into and out of the optical support 1504 at a coupling surface 1516 with a reflective prism surface 1520. An additional prism portion 1512 can be provided

having an input/output surface 1514 and a reflective surface 1518, so that optical inputs and outputs can be associated with different prism portions.

The pointing assembly 1502 includes adjustment mechanisms 1530, 1532, 1534 so that the optical transceiver 1500 can be configured to send and/or receive optical signals from a selected location. The adjustment mechanisms 1530, 1532 include fixed portions 1542, 1544 that are fixed with respect to the optical support 1504, and reference portions 1546, 1548 that are configured for attachment to a mounting surface such as, for example, a window. The adjustment mechanism 1534 can be similarly configured.

With reference to FIG. 16, an optical transceiver 1600 is retained by a pointing assembly 1602 that is configured to direct optical signals to or receive optical signals from a selected location. The optical transceiver 1600 includes an optical support 1604 having an input/output surface 1606 and a focusing surface 1608. A transmit hologram and a receive hologram can be provided on the surface 1606, or a single hologram can be used. The transmit hologram directs an optical signal that is directed from a transmit portion 1610 of a coupling surface 1609 to the surface 1608 and that is then transmitted through the surface 1606. Received optical signals are directed by the receive hologram to the focusing surface 1608 and then directed to a portion 1612 of the coupling surface 1609.

The pointing assembly 1602 includes adjustment mechanisms 1630, 1632, 1634 so that the optical transceiver 1600 can be configured to send and/or receive optical signals from a selected location. The adjustment mechanisms 1630, 1632 include fixed portions 1642, 1644 that are fixed with respect to the optical support 1604, and reference portions 1646, 1648 that are configured for attachment to a mounting surface such as, for example, a window. The adjustment mechanism 1634 can be similarly configured. In representative examples, fixed portions and reference portions are urged toward each other using springs or magnets attached to one or both of the fixed and reference portions.

With reference to FIG. 17, an optical transceiver 1700 includes a diffractive optical element (DOE) 1702 or other light directing element situated at or bonded to a surface 1704 of an optical support 1706. The optical transceiver 1700 is configured to receive an optical signal 1708 through windows 1710, 1712 that are separated by an air gap 1711. As shown in FIG. 17, a surface 1705 of the optical support 1706 is attached to a surface 1713 of the window 1712. In other examples, the optical support 1706 is index matched to the window 1712 with an index-matching material and is retained at the window 1712 with supports that are not shown in FIG. 17. The optical signal 1708 is transmitted to the DOE 1702 and a mirror 1716 or other reflective surface that is aligned with gimbals 1730 so that a diffracted portion 1715 of the reflected optical beam is directed to a reflective region 1717 of the surface 1705 and to an input/output surface 1718 of the optical support 1706. The region 1717 is configured to reflect the diffracted portion 1715 of the optical beam 1708 to the surface 1718. Typically, the reflective region 1717 is provided with a reflective coating such as a metallic or dielectric coating, or a space can be provided between a surface 1720 and the surface 1713 so that the diffracted portion 1715 is substantially reflected by, for example, total internal reflection. If the reflective region 1717 is provided with a reflective coating, it may be convenient to designate a portion of the surface 1704 as an input/output surface. Typically, optical signals are received from or delivered to the optical transceiver 1700 with a segment 1722 of an optical fiber, and an optical beam shape is selected using an optical module 1723 that includes collimating, focusing, or defocusing optics that are generally selected in conjunction with optical power provided in the DOE 1702. Index matching is accomplished with a container 1724 that is configured to retain an index-matching material 1725 such as mineral oil or other index-matching material. Gimbals 1730 are provided for orienting the mirror 1716 for transmission to or reception from a predetermined location. Gimbals for single-axis rotation are shown in FIG. 17, but gimbals for rotation about two or more axes can be provided.

The optical transceiver 1700 is described above with reference to reception of an incoming optical signal, but can also serve to transmit an optical signal received at the input/output surface 1718. As shown in FIG. 17, surfaces of the optical support 1706 are generally planar, but in additional examples, optical power can be provided at one or more surfaces, and transceivers can be configured so that input or output optical beams are reflected and/or focused/defocused at one or more surfaces. In additional examples, a planar or curved mirror or other optical element is adjustable with a kinematic mount, a flexure mount, or other adjustment mechanism. Such reflecting optical elements can be adjusted with respect to one or more axes of rotation to select transmission or reception directions.

With reference to FIG. 18, an optical transceiver 1800 includes a diffractive optical element (DOE) 1802 bonded to a surface 1804 of an optical support 1806. The optical transceiver 1800 is configured to receive an optical signal 1808 through windows 1810, 1812 that are separated by an air gap 1811. As shown in FIG. 18, a surface 1805 of the optical support 1806 is attached to a surface 1813 of the window 1812. The optical beam 1808 is transmitted to the DOE 1802 and a curved mirror 1816 that is aligned with gimbals 1830 so that a diffracted portion 1815 of the reflected optical beam is directed to a reflective region 1817 of the surface 1805 and to an input/output surface 1818 of the optical support 1806. The region 1817 is configured to reflect the diffracted portion 1815 of the optical beam 1808 to the surface 1818. Optical signals are received from or delivered to the optical transceiver 1800 with a segment 1822 of an optical fiber and optical beam shape is selected using an optical module 1823 that includes collimating, focusing, or defocusing optics that are generally selected in conjunction with optical power provided in the DOE 1802 and the curved mirror 1816. Index matching is accomplished with a container 1824 that is configured to retain an index-matching material 1825 such as mineral oil or other index-matching material. Gimbals 1830 are provided for orienting the mirror 1816 for transmission to or reception from a predetermined location. An adjustment screw 1850 and a spring

1852 are provided for selecting an angle of rotation of the mirror 1816, but other adjustment mechanisms such as flexures can be used. Adjustments can be mechanized, and can be based on, for example, detected optical signal power. As shown in FIG. 18, the screw 1850 and the spring 1852 contact the mirror 1816 directly, but generally the mirror 1816 is attached to a mounting plate, mirror mount, or other mounting assembly, and adjustment mechanisms directly contact the mounting plate but not the mirror 1816.

An example optical transceiver 1900 using a reflective hologram 1902 is illustrated in FIG. 19. The hologram 1902 is attached to a rotational mount 1921 and is surrounded by an index-matching liquid 1922 that is contained by an enclosure 1924. At least a portion 1912 of an input optical signal 1908 is directed to an optical support 1907 that includes a curved reflective surface 1910 and a coupling surface 1909. As shown in FIG. 19, a surface 1920 through which optical signals enter and/or exit the optical support 1907 is tilted with respect to the surface 1906. For convenience, refraction of the input optical signal 1908 at the surface 1920 is not shown in FIG. 19, but the optical signal 1908 need not enter the optical support 1908 perpendicularly to the surface 1920. The hologram 1902 is typically configured to deflect optical signals of selected wavelengths to the curved reflective surface 1910 and transmit other wavelengths. In addition, the deflected optical signal portion 1912 typically propagates at an angle greater than a critical angle with respect to the surface 1906. An angle of rotation of the hologram 1902 can be adjusted with the rotational mount 1921 for transmission to or reception from a selected location. In other examples, a hologram can be provided on the surface 1906 and a mirror provided for rotational adjustment.

With reference to FIG. 20, an optical transceiver 2000 includes a hologram 2002 or other light directing element situated at or bonded to a surface 2004 of a window 2005. The optical transceiver 2000 is configured to receive an optical signal 2008 through the hologram 2002, and to direct a diffracted or otherwise deflected portion 2012 of the optical signal to surfaces 2009, 2010 of an optical support 2006. The optical support 2006 includes a first portion 2014 and a second portion 2016 that are

bonded at an interface surface 2018. A surface 2020 is configured to reduce multiple reflections within the optical support 2006 and direct any such reflected light away from a collection region 2022. One or more tilt angles of the optical support 2006 are selectable with a gimbal mount 2030 or other mechanism. An enclosure 2032 is configured to retain an index-matching fluid 2034.

An example optical transceiver 2100 using a reflective hologram 2102 is illustrated in FIG. 21. The hologram 2102 is configured to direct optical beams between an input surface 2120 and an interface surface 2109 using a reflector 2110 that is attached to a rotational mount 2121 and is surrounded by an index-matching liquid 2122 that is contained by an enclosure 2124. At least a portion 2112 of an input optical signal 2108 is directed to the reflector 2110. As shown in FIG. 21, the surface 2120 through which optical signals enter and/or exit an optical support 2107 is tilted with respect to a surface 2106. In a typical installation, the input surface 2120 is bonded to a window with an index matching material such as an optical adhesive, and reflections from the surface 2106 are substantially eliminated so surface tilt is unnecessary. The hologram 2102 is typically configured to deflect optical signals of selected wavelengths to the reflector 2110. The deflected optical signal portion 2112 typically propagates at an angle greater than a critical angle with respect to the surface 2106. An angle of rotation of the reflector 2110 can be adjusted with the rotational mount 2121 for transmission to or reception from a selected location. In some examples, the reflector 2110 is a holographic optical element, and can include optical power for focusing, defocusing, or otherwise controlling optical beams.

Representative examples are described and it will be apparent that these examples can be modified in arrangement and detail. For example, optical supports can include reflective or refractive optical surfaces defined by polished, molded, or machined surfaces of the optical support, or by optical surfaces bonded to surfaces of an optical support. A transceiver can be configured to transmit, receive, or transmit and receive. Two or more diffractive elements can be provided on an optical support for

transmission and reception, respectively. A curved surface can be configured to receive and converge optical signals from a receiver hologram and to deliver optical signals to a transmitter hologram. Such a curved surface can be configured so that received and transmitted optical signals are directed to a first convergence region and received from a second convergence region, respectively. For example, separate fiber cables can be used for received optical signals and for optical signals to be transmitted. A transceiver can include respective holograms for transmit and receive functions, and reflective and/or refractive surfaces can be formed that direct optical signals to and from the respective holograms. Rotations of diffractive optical elements or reflective surfaces can be provided with gimbal mounts, flexures, kinematic mounts or otherwise provided. Various surfaces of optical transceivers can be configured to be rotatable. For example, surfaces 210, 2310, 410, 411 shown in FIGS. 2-4 can be rotatable, or an entire optical support can be rotatable. By providing an optical transceiver with rotatable surfaces, a transceiver can be fixedly attached to, for example, an office window, and a communication direction selected by adjusting one or more rotatable surfaces. In addition, transceivers surfaces can be positioned on a window or otherwise positioned without alignment to a communication direction, and rotatable surfaces adjusted to select the communication direction. In view of these illustrative examples, we claim all that is encompassed by the appended claims.